

Day-night asymmetry of high and low energy solar neutrino events in Super-Kamiokande and in the Sudbury Neutrino Observatory

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Abstract

In the context of solar ν oscillations among active states, we briefly discuss the current likelihood of Mikheyev-Smirnov-Wolfenstein (MSW) solutions to the solar ν problem, which appear to be currently favored at large mixing, where small Earth regeneration effects might still be observable in Super-Kamiokande (SK) and in the Sudbury Neutrino Observatory (SNO). We point out that, since such effects are larger at high (low) solar ν energies for high (low) values of the mass square difference δm^2 , it may be useful to split the night-day rate asymmetry in two separate energy ranges. We show that the difference Δ of the night-day asymmetry at high and low energy may help to discriminate the two large-mixing solutions at low and high δm^2 through a sign test, both in SK and in SNO, provided that the sensitivity to Δ can reach the (sub)percent level.

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I. CURRENT MSW SOLUTIONS: LMA, LOW, SMA

The well-known Mikheyev-Smirnov-Wolfenstein (MSW) [1] solutions to the solar ν problem [2] appear to have a somewhat different likelihood after the most recent data from the Super-Kamiokande (SK) experiment [3], as compared with previous fits [4–6]. The new SK data, both by themselves [3] and in combination with the results of the chlorine (Cl) [7] and gallium (Ga) experiments (SAGE [8], GALLEX and GNO [9]), tend now to favor the so-called large mixing angle (LMA) and low mass (LOW) regions of the parameter space, with respect to the region at small mixing angle (SMA) [3]. This tendency emerges mainly from a “tension” between the flat (normalized) spectrum observed in SK and the prediction of a nonvanishing spectral distortion in the SMA region favored by total rates [3]. However, a compromise between such two discordant indications is still reached in global fits.

Figure 1 shows the results our global 2ν (active) oscillation fit to the latest 39 solar neutrino data, including the three SK, Cl, and Ga total rates [3,7–9], and the two 18-bin day and night SK energy spectra of events [3,10] above 5.5 MeV. We take as free variables the overall spectrum normalization (to avoid double counting of the total SK rate information), the ν mass square difference δm^2 , and the mixing angle ω , parametrized in terms of $\tan^2 \omega$ to cover the full range $\omega \in [0, \pi/4]$ [11]. Details of our calculations and of the χ^2 statistical analysis can be found in [12] and references therein. Subleading quasi-vacuum effects at low δm^2 [13,14], recently revisited in [15], are taken into account as described in [16].

The three local χ^2 minima turn out to be $\chi^2_{\min} = 35.1$ (LMA), 38.7 (LOW), and 40.7 (SMA). This implies, from the point of view of *hypotheses tests* [17] ($N_{\text{DF}} = 39 - 3$), that any of the three solutions is acceptable, since $\chi^2_{\min}/N_{\text{DF}} \sim 1$ in any case. From the point of view of mass-mixing neutrino *parameter estimation* [17] ($N_{\text{DF}} = 2$), the relative likelihood is instead governed by $\Delta\chi^2 = \chi^2 - 35.1$. In Fig. 1, $\Delta\chi^2$ contours at 90%, 95%, and 99% C.L. are shown as thin solid, thick solid, and dotted curves, respectively. The LOW solution emerges at 84% C.L. ($\Delta\chi^2 = 3.6$), while the SMA solution emerges only at 94% C.L. ($\Delta\chi^2 = 5.1$).

Figure 2 shows, for the sake of completeness, the regions favored by fits to total rates (Cl+Ga+SK), and by the SK day-night spectra, at the same C.L.’s as in Fig. 1. As already mentioned [3], a “tension” emerges between the total rate data (which are highly consistent with the SMA solution) and the SK spectral data (which disfavor such solution).¹ However, this tension is not enough to exclude the SMA region yet. In fact, a compromise is reached in the global fit of Fig. 1 where, as compared with Fig. 2, the SMA solution survives at smaller mixing angles, corresponding to smaller spectral distortions. The price to pay is an increase in the C.L. at which the SMA solution emerges (94% in Fig. 1), as compared with previous analyses [4–6].

Summarizing, the LMA and LOW solutions appear to be favored over the SMA solution in the global fit, although it is rather premature to think that the latter is ruled out. In the following, we discuss a possible way to discriminate the two most likely solutions (LMA and LOW) in favorable situations, by separating Earth regeneration effects in two distinct

¹ Notice that, conversely, the LOW solution is disfavored by total rates, but is highly consistent with SK day-night spectra.

energy ranges.

II. A POSSIBLE TEST TO DISCRIMINATE THE LOW AND LMA SOLUTIONS

The slightly positive indication ($\sim 1.3\sigma$) for an excess of nighttime to daytime events in Super-Kamiokande [3], if confirmed with higher statistical significance, would indicate the occurrence of the Earth regeneration effect for ^8B solar neutrinos (see, e.g., [18–22] for recent night-day asymmetry studies in SK). Such indication, by itself, might not be sufficient to discriminate the LMA from the LOW solution, since a slight excess is predicted in both cases. However, it has long been known that the Earth regeneration effect for solar neutrinos is strongly dependent on the neutrino energy [23,24]. Such dependence leads to several effects that might be observed in the Super-Kamiokande experiment [3] and in the Sudbury Neutrino Observatory (SNO) [25], including night-day variations of energy spectrum distortions [18,21,26], or variations of the night-day rate asymmetry with the electron energy threshold [19,20]. In particular, starting from the simple observation that the Earth regeneration effect is stronger at low energy for the LOW solution, and at high energy for the LMA solution,² we point out that it may be useful to study the night-day asymmetry in two separate energy ranges in both SK and SNO.

For definiteness, we consider the two following representative ranges for the total (measured) energy of recoiling electrons in SK (ν - e scattering) and in SNO (ν - d absorption),

$$\text{Low range } (L) = [5, 7.5] \text{ MeV} , \quad (1)$$

$$\text{High range } (H) = [7.5, 20] \text{ MeV} , \quad (2)$$

and calculate the night-day rate asymmetry in such ranges,³

$$A_{L,H} = \left(\frac{N - D}{N + D} \right)_{L,H} . \quad (3)$$

Since one expects $A_H \gtrsim A_L$ for the LMA solution and $A_H \lesssim A_L$ for the LOW solution, it is useful to introduce the difference

$$\Delta = \left(\frac{N - D}{N + D} \right)_H - \left(\frac{N - D}{N + D} \right)_L , \quad (4)$$

which should change sign when passing from the LMA region ($\Delta \gtrsim 0$) to the LOW region ($\Delta \lesssim 0$).

Figures 3 and 4 show the results of our calculations of Δ (eccentricity effects removed) in SK and SNO, respectively, in the form of isolines at $\Delta \times 100 = \pm 0.5$, ± 1 , and ± 2 . Notice

²See, e.g., Fig. 4 of [20].

³The 5 MeV threshold has already been reached in SK, although the [5, 5.5] MeV bin is not used yet in SK fits [3].

that the magnitude of Δ in SNO is typically a factor of two higher than in SK. Figures 3 and 4 confirm that $\Delta > 0$ (< 0) would represent clear evidence in favor of the LMA (LOW) solution, both in SK and SNO, thus allowing a useful “sign discrimination test” to solve the LOW-LMA ambiguity at large mixing. The power of such test decreases as $\Delta \rightarrow 0$ in the upper part (lower part) of the LMA (LOW) solution, corresponding to vanishing Earth regeneration effects for ^8B neutrinos in SK and SNO.

From a comparison of Figs. 1, 3, and 4, it turns out that, in the most favorable case for the LOW solution (i.e., in its upper part), the quantity $\Delta \times 100$ can approximately reach the value -0.5 in SK and -1 in SNO; analogously, it can reach the value $+1$ (SK) and $+2$ (SNO) for the LMA solution. The separation between the two solutions is thus $\Delta(\text{LMA}) - \Delta(\text{LOW}) \lesssim 1.5\%$ in SK ($\lesssim 3\%$ in SNO) and, in its upper range, it seems not too far from the present experimental sensitivity to day-night effects.⁴

In general, however, one should require for detection of $\Delta \neq 0$ a typical sensitivity at the subpercent level in SK, and at the percent level in SNO, whose viability requires not only a very high statistics, but also a dedicated study of systematics (and of their cancellations in a difference like Δ). Notice also that the energy value separating the L and H ranges does not need to be equal to our representative choice (7.5 MeV) nor to be the same in SK and SNO, and should be tuned to optimize the statistical significance of the Δ -sign test. The test would in any case benefit from a reduction of the SK and SNO energy thresholds, which would both increase the statistics and enhance the sensitivity to Earth effects at low energies.⁵ Such detailed experimental studies are beyond the scope of this work, whose main purpose is to emphasize that the difference of the night-day asymmetry at low and high neutrino energy in SK and SNO might be observable in favorable situations, and help to separate the LOW and LMA solutions. Even in the absence of an accurate measurement of Δ , the simple *concordance* of the Δ sign in SK and SNO ($++$ for the LMA solution or $--$ for the LOW solution) would be a valuable information.

III. SUMMARY AND CONCLUSIONS

We have presented a global MSW oscillation fit to the solar neutrino data, showing that all the three usual solutions (SMA, LMA, and LOW) emerge at 95% C.L. The LOW and LMA solutions appear to be globally favored, the latter providing the best fit. Within the LMA (LOW) solution, the excess of nighttime events due to ν_e regeneration in the Earth is larger in the higher (lower) part of the neutrino energy range. Therefore, by taking the difference Δ of the night-day asymmetry in two separate ranges at high and low energy,

⁴The quoted SK uncertainty on $A = N - D/N + D$, integrated over the full energy range, is $\pm 1.1\%$ (stat.) $\pm 0.6\%$ (syst.) [3]. The (larger) total uncertainty of A_H and A_L in the two H and L energy sub-ranges is presumably at the $\sim 2\%$ level, although we have not enough information for a precise estimate.

⁵Experiments sensitive to neutrino energies below the SK or SNO threshold can also observe relevant day-night effects in the LOW region [27] (see also [4,20] and references therein).

a small positive (negative) signal would provide evidence for the LMA (LOW) solution. Detection of $\Delta \neq 0$ requires a (sub)percent sensitivity to day-night effects, which needs to be assessed by further experimental investigations. However, the simple preference (and concordance) of the SK and SNO experiments for a definite Δ sign would already provide us with valuable information, corroborating other tests envisaged to solve the LOW-LMA ambiguity in such experiments [26].

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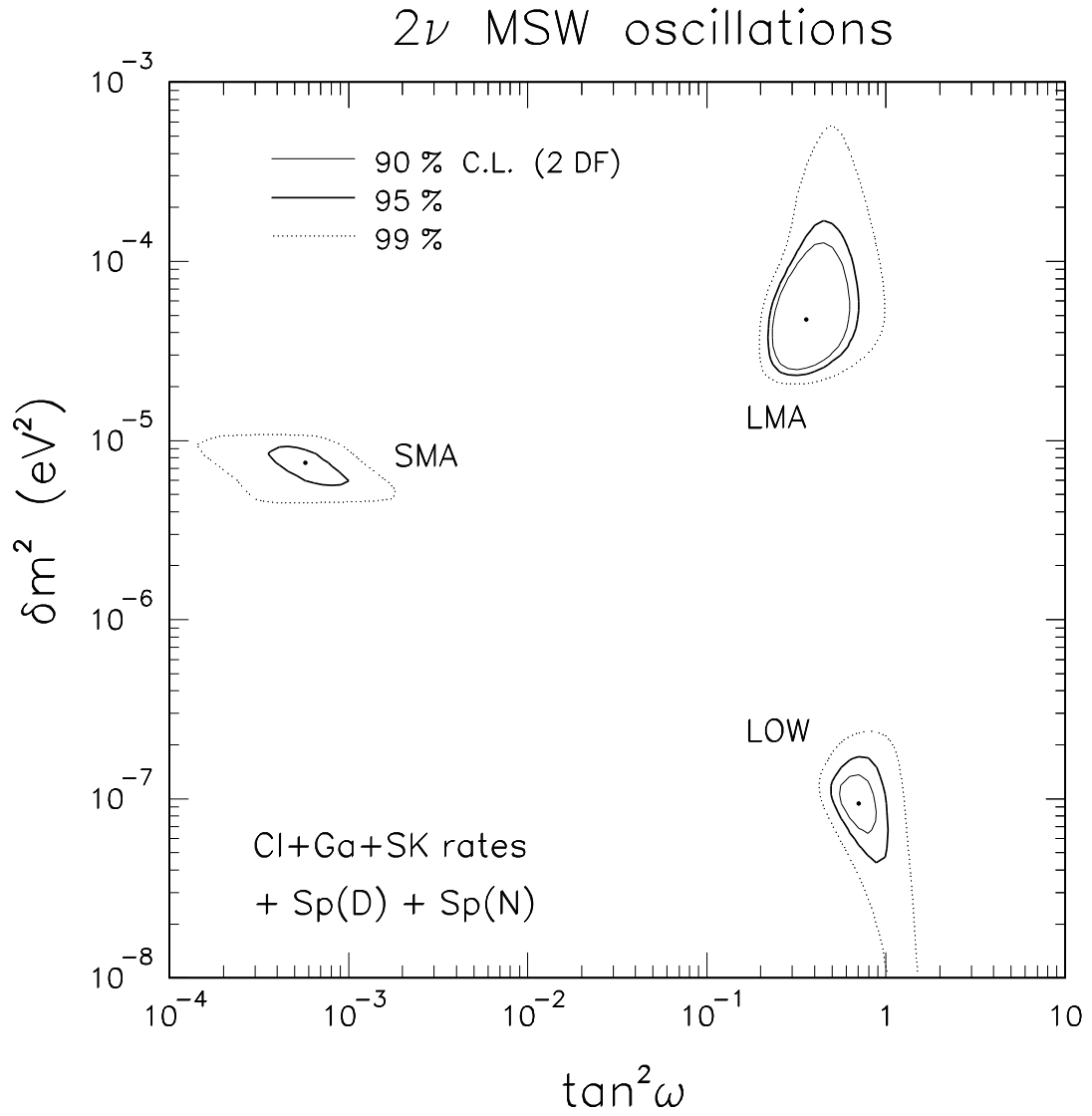


Fig. 1. Global 2ν fit including total solar neutrino rates (Ga+Cl+SK) [3,7–9] and the SK day and night spectra [3,10].

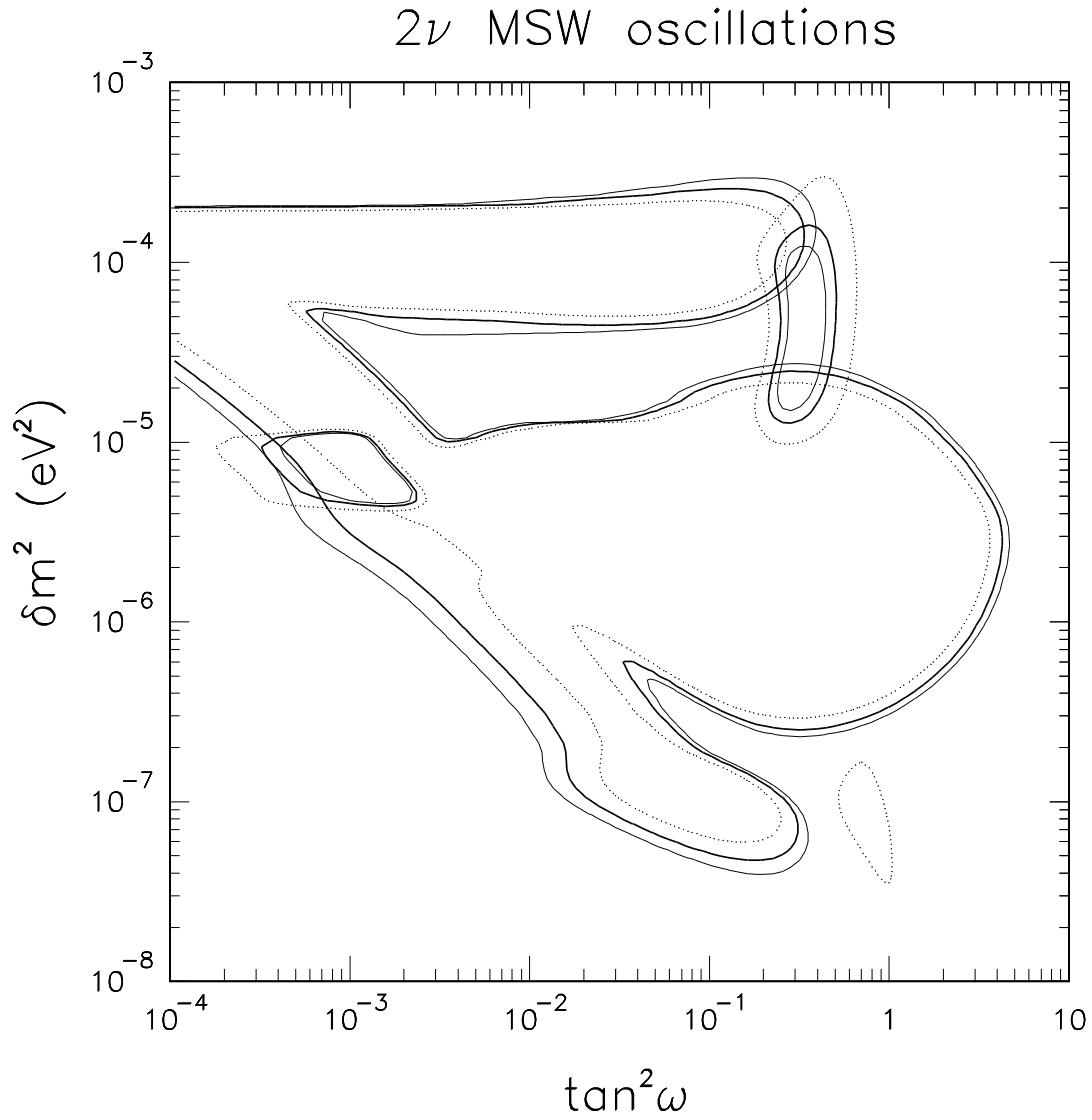


Fig. 2. Results of the separate fits to total rates and to SK day-night spectra. Total rate data mainly determine the three SMA, LMA, and LOW allowed regions, while the SK day-night spectra exclude a large part of the parameter space where either spectral distortions or day-night effects are large.

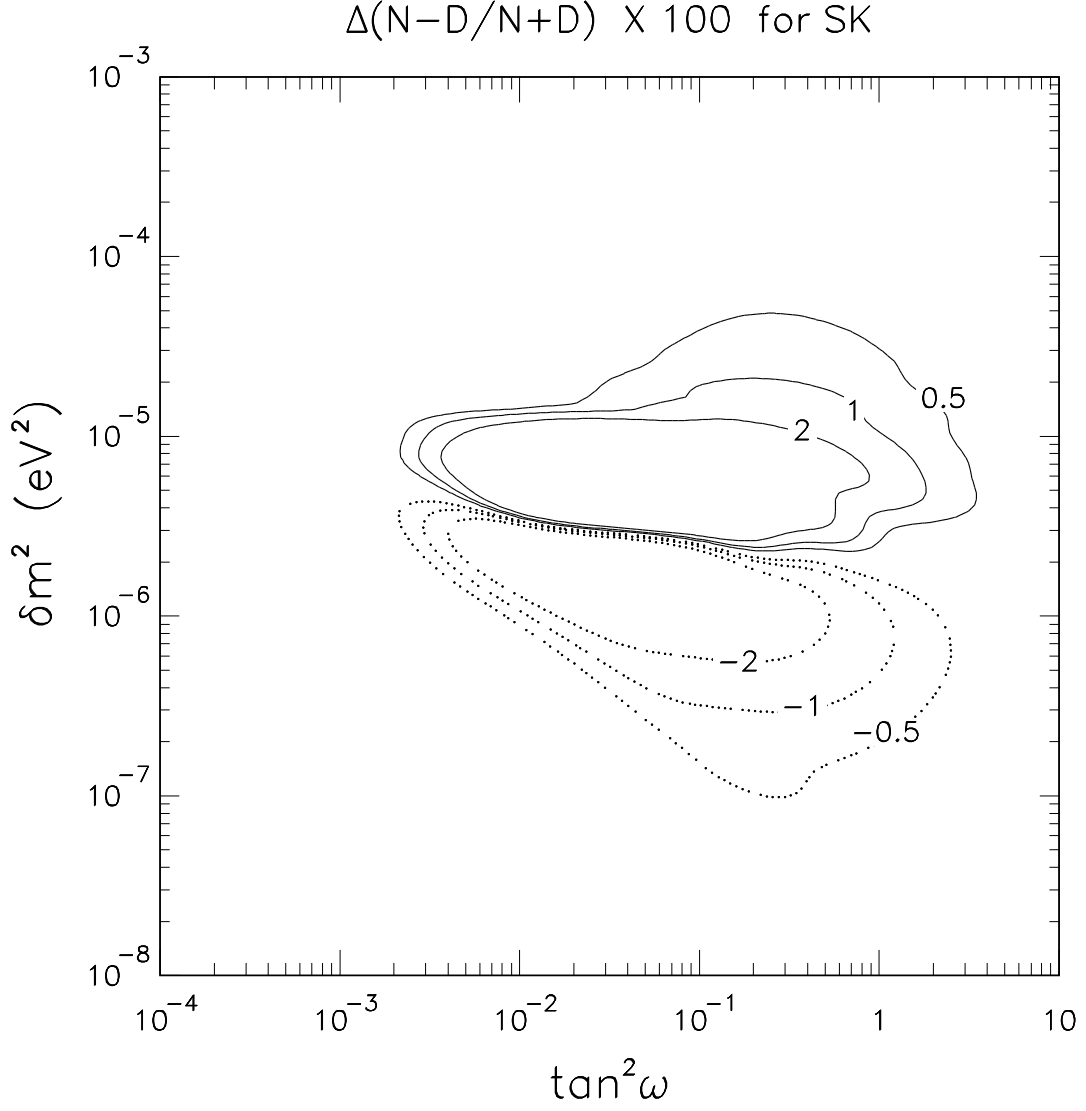


Fig. 3. The difference Δ between the night-day asymmetry calculated in the two ranges $[7.5, 20]$ and $[5, 7.5]$ MeV for the SK detector ($\times 100$). Solid and dotted curves refer to $\Delta > 0$ and < 0 , respectively. The LOW and LMA solutions in Fig. 1 predict opposite signs for Δ .

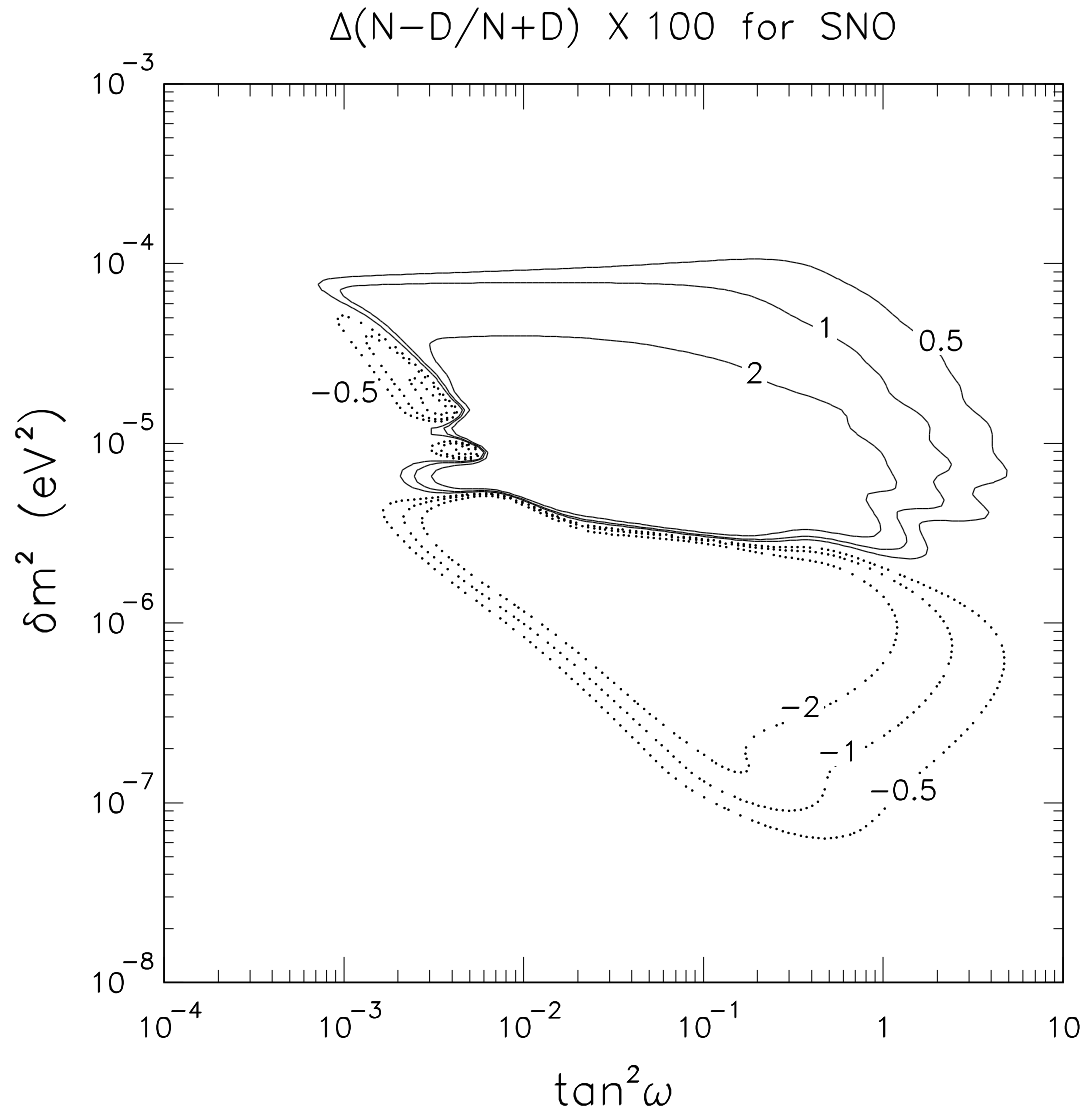


Fig. 4. As in Fig. 3, but for the SNO detector.